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Asymmetric GaAs/AlGaAs *T* wires with large confinement energies

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We report on the design and growth of asymmetric *T*-shaped quantum wires with large one-dimensional confinement energies. Prior to growth, the optimal structure for a given (110) well width is determined by a calculation. The structures are made by molecular beam epitaxy cleaved edge overgrowth. We demonstrate a confinement of 54 meV in an experimental structure consisting of a narrow (110) oriented $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well overgrown on much wider (001) oriented $Al_{0.14}Ga_{0.86}As/Al_{0.3}Ga_{0.7}As$ wells. © *1996 American Institute of Physics.* [S0003-6951(96)03747-3]

One-dimensional wire states confined at the intersection between (001) and (110) oriented GaAs/AlGaAs quantum wells (*T* wires) are predicted to have enhanced exciton binding energies and oscillator strengths compared to two-dimensional structures.[1] These one-dimensional structures have been realized by the cleaved edge overgrowth technique[2] with monolayer precision determined by the molecular beam epitaxy (MBE) growth technology. The fundamental properties of the one-dimensional systems together with their potential device applications have led to a strong interest in the growth and optimization of these structures.[3–6]

The size of the one-dimensional confinement energy is of great importance for device applications at room temperature. The highest *T*-wire confinement energies reported are, to our knowledge, 28 meV for asymmetric GaAs/AlGaAs *T*-wire with Al in the (001) wells[4] and 38 meV for asymmetric GaAs/AlAs *T* wires.[7]

We present in this work an optimization of asymmetric GaAs/AlGaAs *T* wires with a low concentration of Al in the (001) wells and reach a *T*-wire confinement energy of 54 meV, which is significantly higher than kT at room temperature. We pre-design the sample parameters by a calculation of the confined *T*-wire states.[8] The calculations are based on an effective mass approach for the conduction band states and a six-band $\mathbf{k}\cdot\mathbf{p}$ model for the valence band states. Here we show, in Fig. 1(a), the results for the transition energies of asymmetric *T* wires with $Al_{0.3}Ga_{0.7}As$ barriers. The calculations are made for *T* wires with 3- and 5-nm-wide overgrown GaAs wells. For a given overgrown well width, the transition energy of the *T* wires is evaluated as a function of the (001) oriented $Al_xGa_{1-x}As$ well width. The Al content (x) of the (001) wells, shown in Fig. 1(b), is adjusted for each well width so that the transition energy of the (001) wells coincides with the transition energy of the (110) well, indicated by the solid horizontal lines in Fig. 1(a). The highest one-dimensional confinement energy is found where the separation between the transition energy of the *T* wires and the wells is largest.

The general trend, seen in Fig. 1(a), is that the *T*-wire transition energy is lowered with increasing (001) well width until a second confined *T*-wire state appears with higher energy. In this case, the effective confinement is reduced to the separation between the first and second *T*-wire state. Therefore, we choose a sample design with only one *T*-wire state. The optimized sample parameters are taken from Figs. 1(a) and 1(b), and the corresponding structures are shown in Fig. 1(c). In this way, we expect one-dimensional confinement energies of 26 meV for the 5 nm overgrowth and 34 meV for the 3 nm overgrowth.

Using MBE, we have grown two asymmetric *T*-wire samples (ASW1 and ASW2) similar to the calculated optimized structures, which are 3 and 5 nm (110) $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells overgrown on 120 Å $Al_{0.12}Ga_{0.88}As/Al_{0.3}Ga_{0.7}As$ and 180 Å $Al_{0.07}Ga_{0.93}As/Al_{0.3}Ga_{0.7}As$ (001) oriented multiple quantum wells, respectively.

The growth of the (001) structure is somewhat compli-

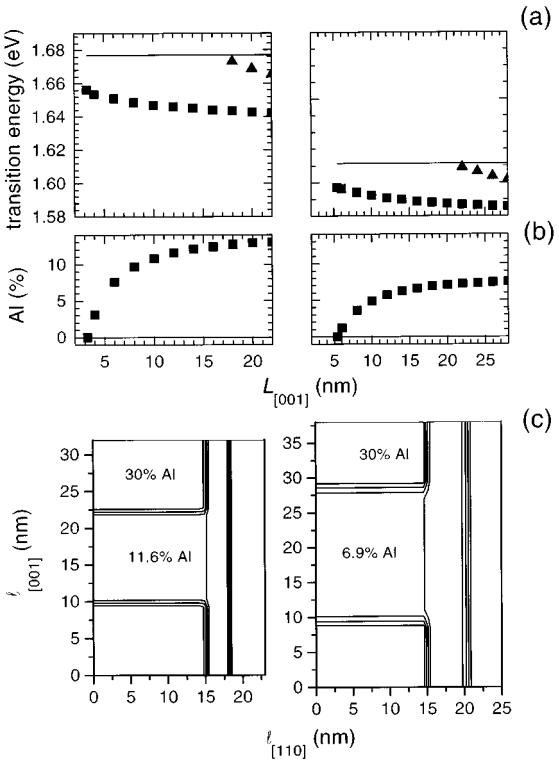

FIG. 1. Calculated transition energies (a) and Al contents (b) of *T* wires with 3 nm (left) and 5 nm (right) (110)-$GaAs/Al_{0.3}Ga_{0.7}As$ overgrowth for different (001) $Al_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ well widths. The optimized sample structures are shown in (c).

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cated by the low Al content in the wells. Having only one Al cell in the MBE growth chamber, this structure can either be made by growth interrupts, while the temperature of the Al cell is changed between the growth of the barriers and the growth of the wells, or by keeping the temperature of the Al cell fixed and rapidly operating the shutter of the Al cell, thus forming a digital alloy (DA) in the wells.[4] We chose the latter approach to avoid surface contamination during growth interrupts. However, it imposes an inaccuracy in the value of the Al content in the wells, because the nominal Al shutter time is comparable to the shutter switching time (specified to 0.3 s). To compensate for this inaccuracy, we characterize the DA wells before the cleaved edge overgrowth is performed to determine the actual transition energy and to adjust the thickness of the overgrown well correspondingly.

The nominal 7% DA of ASW2 was grown by dividing the 180 Å wells into 20 sublayers of 9 Å. Each sublayer is then divided into a GaAs layer and an $Al_{0.3}Ga_{0.7}As$ layer. The width of the $Al_{0.3}Ga_{0.7}As$ layer is given by the ratio between the intended Al content of the DA to the Al content of the barrier, multiplied by the width of the sublayer. This gives 2.1 Å for the $Al_{0.3}Ga_{0.7}As$ layer, leaving 6.9 Å for the GaAs layer. The Al shutter was opened 20 times for 0.64 s per quantum well. The rotation of the substrate during growth was fast enough to give one rotation per 2.1 Å $Al_{0.3}Ga_{0.7}As$ layer. The barrier width is 320 Å in order to decouple the *T*-wire states. The total thickness of the (001) structure is 2.5 μm. The (001) structure of sample ASW1 was made similarly, with a nominal 12% DA in the 120-Å-thick wells, which were divided into 10 sublayers. This structure consists of 20 wells separated by 200-Å-thick barriers and is 0.64 μm thick.

Low-temperature photoluminescence (PL) measurements were performed with the samples mounted in a continuous-flow cryostat using He–Ne (632.8 nm) or Ar-ion (488 nm) laser excitation, both with an excitation intensity of 0.1 W/cm^2. The PL was dispersed in a spectrometer and detected by a photomultiplier using photon counting techniques. To adjust the sample position, the PL was imaged with a video camera.

The PL spectra of the (001) structures, measured at 4 K, are displayed in Fig. 2 and show the heavy-hole exciton emission from the wells. The linewidths are 3 and 5 meV for the DA of ASW2 and ASW1, respectively. The transition energies of the DA wells are mainly given by the alloy bandgap,[9] $E_g = 1.519 + 1.155x + 0.37x^2$, because the quantization energies for the large well widths are low, e.g., 10 meV for the 180 Å well of ASW2. From the transition energies in Fig. 2, we estimate a higher Al content of about 9% and 14% instead of the nominal 7% and 12%.

Taking the above characterization into account, the cleaved edge overgrowth of the (110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ well is designed so that the transition energy of the well coincides with the transition energy of the experimentally realized (001) wells. The transition energies of the (110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ wells, as a function of well width, have been calculated previously and experimentally verified.[10]

The substrates of the (001) structures were lapped to a thickness of 90 μm to ease the cleaving. Pieces of 5×6 mm^2 were mounted vertically on a special sample holder[5] and cleaved in the MBE buffer chamber to avoid oxidation of the cleaved layers. The overgrowth was started within a few minutes after the cleavage. For ASW1, the overgrowth is a 25 Å well, a 200 Å barrier, and a 100 Å GaAs layer. For ASW2, it is a 43 Å well, a 320 Å barrier, and a 1500 Å GaAs cap.

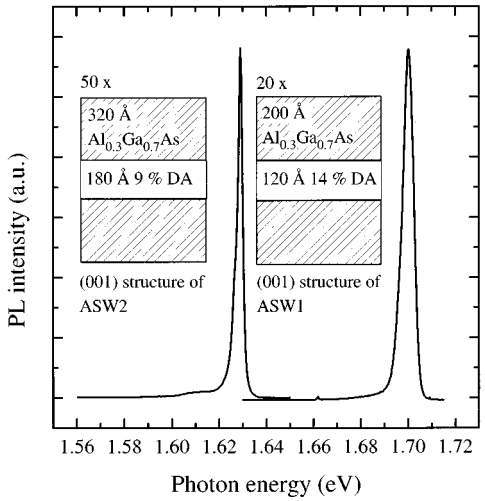

FIG. 2. PL spectra of the (001) structures with a DA in the wells recorded at 4 K. Structure parameters are shown.

Different (110) growth conditions were tested for the two samples. For ASW1, a low substrate temperature of about 460 °C and a low GaAs growth rate of 0.5 μm/h was used. The V/III beam equivalent pressure (BEP) ratio was 30. For ASW2, the GaAs growth rate was 0.45 μm/h and the substrate temperature was increased to about 500 °C to compensate for a possible temperature difference between the cleaved edge and the planar substrate.[11] The temperatures were measured by an infrared pyrometer on a planar reference substrate.

The PL spectra of the two *T*-wire structures are shown in Fig. 3. The PL intensity of the wires is almost constant be-

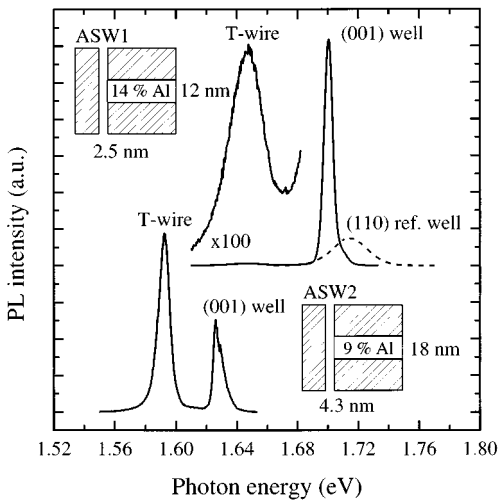

FIG. 3. Sample structures and PL spectra of the *T*-wire structures ASW1 and ASW2 recorded at 40 K with He–Ne and argon-ion laser excitation, respectively. The dashed curve is a PL spectrum of a (110) reference structure for the overgrowth of ASW1.

tween 4 and 40 K while the PL of the wells is significantly lowered. This enhances the *T*-wire intensity relative to the well intensity at 40 K. The spectrum of ASW1 shows the heavy-hole exciton emission from the wells, and the *T*-wire emission. The dashed curve is the PL spectrum of a reference structure grown on a planar (110) substrate. The transition energies of the (001) and (110) oriented wells are matching within 10 meV and the *T*-wire states are confined by 54 meV as compared to the (001) well states. The calculated confinement energy between the well and wire states, from Fig. 1(a), is 35 meV for the pre-designed structure. For the actual structure ASW1, the calculated confinement is 39 meV.

For ASW2, the *T*-wire PL is separated by 37 meV from the PL of the (001) wells, and the temperature dependence above 50 K (not shown) of the *T*-wire PL intensity shows an activation energy of 32 meV. The *T*-wire confinement energy is thus between 32 and 37 meV, while the calculated *T*-wire confinement energy of ASW2 is 28 meV.

The difference between the calculated and measured *T*-wire confinement energies may have several reasons. First, the accuracy of the calculation is limited by the accuracy of the material parameters, the theoretical model, and our knowledge about the precise shape of the *T*-wire structure. Second, Coulomb interaction and strain shifts are neglected in the calculations of both the well and *T*-wire states.

The exciton binding energy of the 120 (180) Å thick (001) well is about 9 (8) meV,[12] respectively. Thus, a *T*-wire exciton binding energy of approximately 25 (17) meV would explain the enhanced confinement in terms of the Coulomb interaction. Previously, *T*-wire exciton binding energies of 20 and 16 meV have been calculated[1] for structures which are different, but similar to the structures ASW1 and ASW2, in fair agreement with the values 25 and 17 meV. Recently, *T*-wire exciton binding energies of 17 and 27 meV have been reported for GaAs *T*-wires with $Al_{0.3}Ga_{0.7}As$ and AlAs barriers, respectively.[7] In general, these values are higher than expected from calculations of the exciton binding energy in *T*-wire structures.[13] Also, other mechanisms such as strain shifts and unequal overgrowth on well and barrier regions of the cleaved (001) multiple quantum well could account for the enhanced *T*-wire confinements compared to calculation.

The PL linewidth of the (110) reference is 24 meV due to the narrow well width.[10] Since the *T*-wire state is a mixture of the (001) and (110) well states, the linewidth is expected to be in-between the linewidths of these wells. In fact, the 20 meV *T*-wire PL linewidth of ASW1 is in good agreement with the calculated 75% of the linewidth of the (110) well.[8] In the spectra of ASW2, the *T*-wire linewidth is only 7 meV. We estimate a 10 meV PL linewidth of the 43 Å (110) well from previous studies of the (110) wells.[10] The linewidth of the *T*-wire emission is thus also about 75% of the PL linewidth of the (110) well.

The differences in the relative PL intensities for ASW1 and ASW2 are caused by the different substrate temperature and cap layer thickness in the overgrowth. This has been verified by a regrowth of the structure ASW1 using only a higher substrate temperature in one case, and in the other case also a thicker GaAs cap layer, as in the overgrowth of ASW2. The relative wire intensity was enhanced by a factor of 4 (100), in the first (second) case, respectively. The strong dependence of the wire PL on the cap thickness was not expected, because the tunneling of the carriers to the surface is controlled by the barrier thickness. It may, however, be related to the influence of surface fields or to a change of the radiative coupling in the proximity of the surface.

In conclusion, a systematic approach to improve the confinement energy of *T*-wires has been demonstrated. The sample parameters were pre-designed by the use of a numerical calculation of the confined *T*-wire states. After PL characterization of the (001) oriented DA wells, the overgrown well thickness was adjusted to match the (110) and (001) transition energies. By this procedure, a confinement energy of 54 meV is achieved, which is significantly larger than the previously reported 38 meV.[7]

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[1] Y. C. Chang, L. L. Chang, and L. Esaki, Appl. Phys. Lett. **47**, 1324 (1985).
[2] L. N. Pfeiffer, K. W. West, H. L. Störmer, J. P. Eisenstein, K. W. Baldwin, D. Gershoni, and J. Spector, Appl. Phys. Lett. **56**, 1697 (1990).
[3] D. Gershoni, J. S. Weiner, S. N. G. Chu, G. A. Baraff, J. M. Vandenberg, L. N. Pfeiffer, K. W. West, R. A. Logan, and T. Tanbuk-Ek, Phys. Rev. Lett. **65**, 1631 (1990).
[4] A. R. Goñi, L. N. Pfeiffer, K. W. West, A. Pinczuk, H. U. Baranger, and H. L. Störmer, Appl. Phys. Lett. **61**, 1956 (1992).
[5] L. N. Pfeiffer, H. L. Störmer, K. W. Baldwin, K. W. West, A. R. Goñi, A. Pinczuk, R. C. Ashoori, M. M. Dignam, and W. Wegscheider, J. Cryst. Growth **127**, 849 (1993).
[6] W. Wegscheider, L. N. Pfeiffer, M. M. Dignam, A. Pinczuk, K. W. West, S. L. McCall, and R. Hull, Phys. Rev. Lett. **71**, 4071 (1993).
[7] T. Someya, H. Akiyama, and H. Sakaki, Phys. Rev. Lett. **76**, 2965 (1996).
[8] W. Langbein, H. Gislason, and J. M. Hvam, Phys. Rev. B (to be published).
[9] S. Adachi, *Properties of Aluminum Gallium Arsenide* (INSPEC, London, 1993).
[10] H. Gislason, C. B. Sørensen, and J. M. Hvam, Appl. Phys. Lett. **69**, 800 (1996).
[11] T. Someya, H. Akiyama, and H. Sakaki, J. Appl. Phys. **79**, 2522 (1996).
[12] E. S. Koteles and J. Y. Chi, Phys. Rev. B **37**, 6332 (1988).
[13] W. Langbein and J. M. Hvam, (unpublished).